

THE PHYSICAL STATE OF THE INTERGALACTIC MEDIUM OR CAN WE MEASURE y ?

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ABSTRACT

We present an argument for a *lower limit* to the Compton- y parameter describing spectral distortions of the cosmic microwave background (CMB). The absence of a detectable Gunn-Peterson signal in the spectra of high redshift quasars demands a high ionization state of the intergalactic medium (IGM). Given an ionizing flux at the lower end of the range indicated by the proximity effect, an IGM representing a significant fraction of the nucleosynthesis-predicted baryon density must be heated by sources other than the photon flux to a temperature $\gtrsim \text{few} \times 10^5 K$. Such a gas at the redshift of the highest observed quasars, $z \sim 5$, will produce a $y \gtrsim 10^{-6}$. This lower limit on y rises if the Universe is open, if there is a cosmological constant, or if one adopts an IGM with a density larger than the prediction of standard Big Bang nucleosynthesis.

1. Introduction

Arriving from high redshift, the photons of the cosmic microwave background (CMB) carry information on the state of the material through which they have traveled, in particular the intergalactic medium (IGM). Any interaction at low redshifts between the IGM and the photons leads to a characteristic spectral distortion of the CMB commonly referred to as the *Compton y -distortion* (Zel'dovich & Sunyaev 1969), due to its physical origin in Compton scattering between electrons and photons and the fact that it is described by a single number called the y parameter (defined below). The deviation from a pure blackbody appears in the Wien tail of the CMB, in the far infrared at wavelengths from about 1 mm to 100 microns. Observations of this background thus provide constraints on the density and temperature of the ionized component of the IGM; an upper limit on y places *upper* limits on the temperature and density. The current limit from FIRAS is $y < 2.5 \times 10^{-5}$ (Mather et al. 1994).

Studies of quasar spectra also provide information on the IGM: the absence of a detectable Ly α absorption trough indicates that the IGM contains extremely little neutral Hydrogen (Gunn & Peterson 1965). This so-called Gunn-Peterson (GP) test places stringent limits on the quantity of HI found in the IGM since a redshift of about 5 and forces us to conclude that either there is no uniformly distributed IGM or that it is very highly ionized. For an assumed total (non-zero) IGM density, the GP test thus provides a *lower* limit to the temperature of the ionized component.

As these two types of observations constrain the IGM in the temperature-density plane in *opposite* directions, one may hope to draw interesting conclusions concerning the physical state of the IGM by combining the two types of studies. This is what we shall explore in this contribution by asking the question “given the GP limits, what is the corresponding lower bound to y ?”

2. The Observables

The two observational quantities under consideration are the optical depth to Ly α absorption and the Compton parameter y . For an observed frequency ω_0 , the former may be written as an integral along the photon path, $\omega(z) = \omega_0(1+z)$, up to the redshift z_{qso} of the quasar under observation (we write our equations in units for which $c = k = h/2\pi = 1$):

$$\tau[\Omega_{\text{igm}}, T, J_{24}; H_0, \Omega, \Lambda] = \int_0^{z_{\text{qso}}} dz \left| \frac{dt}{dz} \right| n_{\text{HI}}(z) \sigma_{\alpha}[\omega(z)], \quad (1a)$$

where $\sigma_{\alpha}(\omega)$ is the absorption cross-section; n_{HI} is the density of neutral Hydrogen; Ω_{igm} is the mass density of the IGM relative to the critical density – $n_{\text{igm}} = \Omega_{\text{igm}}(3H_0^2/8\pi G)/m_p$, m_p being the proton mass (in our simple calculation we consider only Hydrogen in the IGM); T is the temperature of the IGM and J_{24} is the photon flux at the Hydrogen ionization threshold in units of 10^{-24} W/m² Hz ster (in more sane units of cgs, and not the PC units enforced during the conference, this corresponds to the familiar J_{21} !). Studies of the proximity effect around quasars suggest that $J_{24} \sim 0.3 - 3$ (Bajtlik et al. 1988), although estimates of the quasar contribution to the ionizing background favor values at the low end of (in fact below) this range (Madau 1992). The function $|\frac{dt}{dz}|$ contains all of the cosmological parameters: Ω , the total mass density of the universe; H_0 , the Hubble constant (hereafter $H_0 = 100h$ km/s/Mpc); and Λ , a possible cosmological constant. If we restrict ourselves for a moment to the case of a critical universe ($\Omega = 1$), this expression reduces to

$$\tau = 4.4 \times 10^5 (1 - \chi) (\Omega_{\text{igm}} h^2) h^{-1} (1 + z)^{1.5}, \quad (1b)$$

in which appears the *ionized* H fraction $\chi(\Omega_{\text{igm}}, T, J_{24})$. This ionized fraction is defined as n_p/n_{igm} , where n_p is the density of free protons. We have explicitly written the dependence on IGM density in terms of $\Omega_{\text{igm}} h^2$ for comparison with the predictions of Big Bang nucleosynthesis theory. This theory constrains the number $\Omega_{\text{bbn}} h^2 \sim 0.013$ (Walker et al. 1991). We see immediately that for any non-negligible quantity of intergalactic gas, χ must be very close to unity to avoid producing an observable amount of absorption, *i.e.* the medium must be highly ionized. This in turn implies, as we will quantify in the following section, a high temperature, particularly for the low fluxes J_{24} suggested by integration of quasar emission. For our purposes, the most useful limits on τ have been given by Giallongo et al. (1994): $\tau < 0.05$ at $z = 4.3$.

The Compton parameter is defined as the integral along the line-of-sight of the Compton optical depth times an effective energy transfer coefficient T/m_e , where m_e is the electron mass:

$$y[\Omega_{\text{igm}}, T; \Omega, H_0, \Lambda] = \int_0^{z_{\text{qso}}} dz \left| \frac{dt}{dz} \right| \left(\frac{T}{m_e} \right) \chi n_{\text{igm}} \sigma_T, \quad (2a)$$

which for a critical universe becomes (σ_T being the Thompson cross-section)

$$y = 10^{-6} T_4 (\Omega_{\text{igm}} h^2) h^{-1} \left(\frac{1+z}{6} \right)^{1.5}. \quad (2b)$$

In the second expression we have defined T_4 as $T/10^4$ K and assumed that $\chi = 1$. Notice also that the numerical value is referred to a redshift of 5.

From these formulae, we easily see the physics helping us to constrain the IGM. A limit on τ eliminates high density, *low* temperature regions of the IGM temperature-density plane while limits on y eliminate high density, *high* temperature regions of this phase space (figures 1 and 2). Thus we “squeeze” the IGM into the left-most portions of the diagram, towards low total IGM density. The redshift dependence in equations (1) and (2) provides motivation to search for the GP effect at the highest possible redshifts, although one must remember that the increasing Ly α forest line density makes this a more and more difficult proposition (beyond the primary difficulty of finding such high redshift quasars). All of this assumes that we know the dependence of χ on the density and temperature of the IGM, or, in other words, that we know the ionization mechanism. In the following section we consider ionization by collisions and radiation.

A remark on the dependence of the constraints on the cosmological model, which enters only through the expansion time dt/dz – All models for which $\Omega < 1$, with or without a cosmological constant, result in tighter constraints on the IGM: The slower deceleration in these scenarios implies a longer expansion time at any given redshift z (dt/dz at any given z increases relative to the critical case) and therefore larger optical depths to *both* Ly α absorption and Compton scattering. Lowering the Hubble constant for a fixed, physical IGM density, $\Omega_{\text{igm}} h^2$, has the same effect. In both case the reason is the same – the Universe is older.

3. Constraints

To proceed and actually constrain the IGM, we must model the ionization physics of the gas, in order to find the functional form of $\chi(\Omega_{\text{igm}}, T, J_{24})$. Assuming ionization equilibrium maintained by a flux of ionizing photons and by collisions, we write

$$\alpha n_p^2 = \Gamma_{\text{pi}} n_{\text{HI}} + \Gamma_c n_p n_{\text{HI}}, \quad (3)$$

where α is the recombination rate; Γ_{pi} , the photoionization rate, dependent on J_{24} ; and Γ_c , the collisional ionization rate. Recall that we consider only Hydrogen in our simple calculation. The assumption of ionization equilibrium eliminates any dependence on the state of the medium prior to the redshift under consideration. Although the recombination rate is smaller than the expansion rate at redshifts less than about 5, this assumption seems reasonable because even the small quantity of gas capable of recombining in one expansion time would quickly violate the GP limits if there were no compensating source of ionization.

To get a feel for the numbers, consider the case of pure photoionization in a critical Universe with $h = 1/2$. Putting $\Gamma_c = 0$, $\Gamma_{\text{pi}} \sim 4 \times 10^{-12} J_{24} \text{ s}^{-1}$ and $\alpha \sim 4 \times 10^{-13} T_4^{-0.7} \text{ cm}^3 \text{ s}^{-1}$ (Peebles 1993) in equation (3), one finds $(1 - \chi)/\chi^2$, and, with the approximation that $\chi \approx 1$, one then arrives (Eq. 1b) at $\tau = 2 \times 10^3 (\Omega_{\text{igm}} h^2)^2 h^{-1} T_4^{-0.7} J_{24}^{-1} [(1+z)/6]^{4.5}$. Thus, in order to satisfy $\tau < 0.05$ at a redshift of 5, an IGM with a density $\sim \Omega_{\text{bbn}} = 0.013/h^2$ subjected to an ionizing flux $J_{24} \sim 1$ must have a temperature of $T_4 \gtrsim 50$. This same gas would then produce a $y \gtrsim 10^{-6}$. Results of a more general and careful calculation, taking into account both photoionization and ionization by collisions, are shown

in the figures.

4. Conclusion

The goal of our discussion is to show the nature of the constraints imposed on the IGM by combining the GP test with limits on the y parameter. The quantitative results are given in the figures for the current GP and y limits, as well as for an eventual limit of $y < 10^{-6}$. Spectral observations of the CMB with the latter sensitivity would either provide the evidence for or eliminate the possibility of hiding a large quantity of baryons in the IGM. This would be an important result for some cosmological scenarios, such as the PIB model (Peebles 1987a; 1987b), and of special interest in light of the cluster “baryon crisis” (White et al. 1993). At a level of $y \sim 10^{-6}$, one is at the threshold of eliminating an IGM containing most of the baryons predicted by standard nucleosynthesis, particularly for low density Universes (figure 2). Such a conclusion would have important implications for the nature of the dark matter in galactic halos. There is the additional hope of improving the GP limits with high resolution spectra of quasars at ever larger redshifts. A combined effort of this kind would permit us to draw interesting and important conclusions on the history of the baryonic content of the Universe during galaxy formation.

References

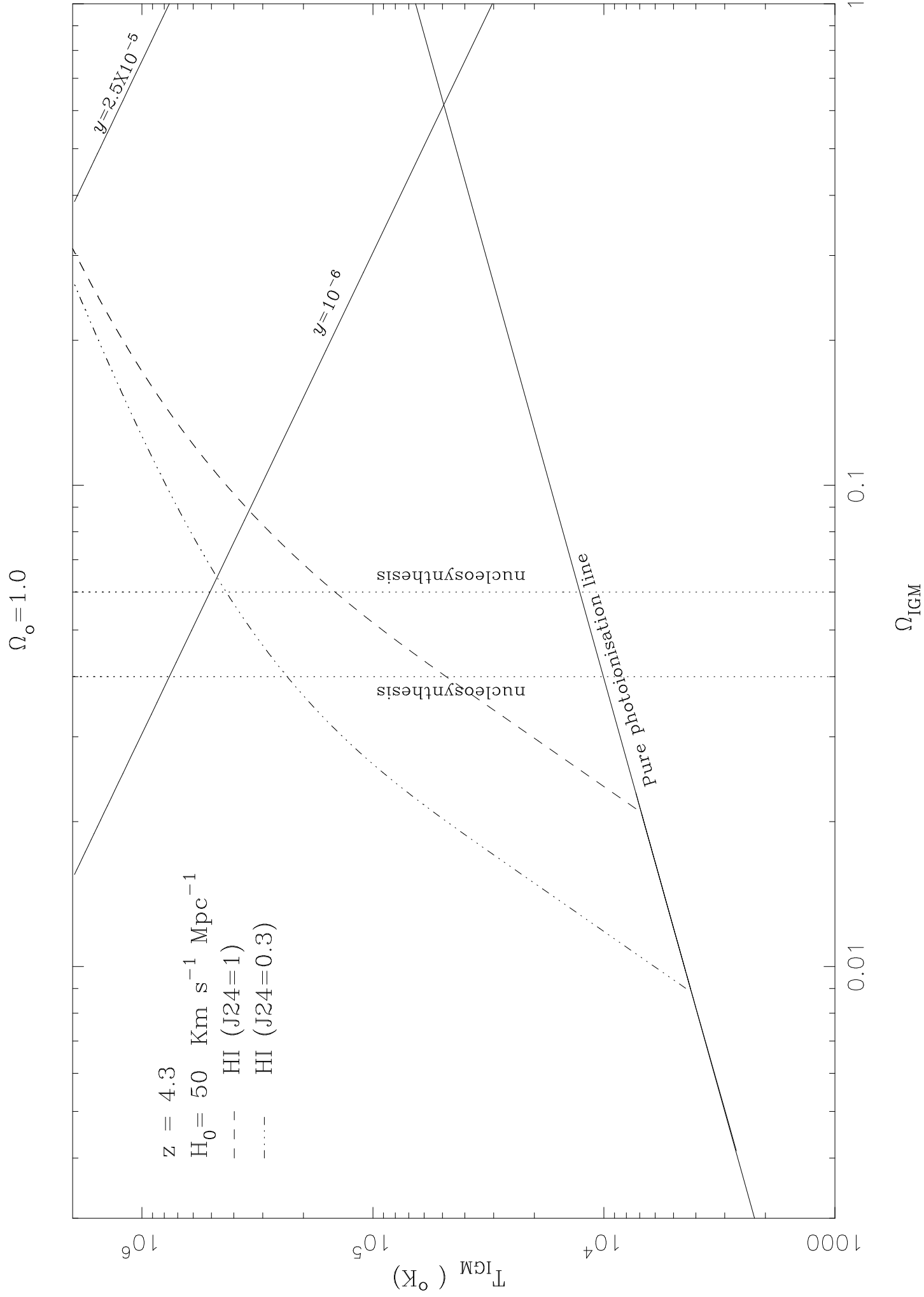
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Figure Captions

Figure 1 The constraints in the temperature-mass plane of the IGM for a flat universe with a Hubble constant of 50 km/s/Mpc. The Giallongo et al. (1994) GP limit ($\tau < 0.05$ at $z = 4.3$) eliminates the space below and to the right of the dashed curve. The calculation accounts for ionization by both collisions and an ionizing flux of $J_{24} = 1$. The change in slope along this curve at the higher temperatures signals the increasing importance of collisional ionization. The dotted-dashed curve shows the corresponding boundary for a flux $J_{24} = 0.3$; this flux is more in line with estimates of the quasar contribution to the ionizing background (Madau 1992). The constraints imposed by observations of the CMB are drawn for the actual FIRAS limit and for a limit of $y < 10^{-6}$. These

constraints eliminate the space above and to the right of the respective curves. Big bang nucleosynthesis bounds the baryon density to the range indicated by the vertical dotted lines. The straight line labeled *Pure photoionisation line* gives the minimum temperature possible for the medium at a given τ (here = 0.05), corresponding to the case where the gas is only heated by the ionizing photons; it is parameterized by J_{24} . For this reason, we see the dashed and dotted-dashed curves terminate at two different points along this line.

Figure 2 Same as figure 1 for $\Omega = 0.1$. Note the change of scale along the abscissa.



$\Omega_o=0.1$

